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DEFORMATION OF PORCELAIN ARTICLES

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The deformation behavior of porcelain and half-porcelain samples during calcination with different type of loads — bending, tension, and torsion — is investigated. The temperature dependences of the effective viscosity of the materials are calculated. The simplest method of determining the deformation stability is bending cantilevered samples, and the most informative and accurate method is torsion of thin-wall tubes.

The drive to decrease calcination time and temperature by using active fluxes and the more stringent requirements imposed on the dimensional exactitude of ceramic articles are making investigations of the deformation of ceramic articles increasingly more urgent.

Three basic groups of factors have a large effect on the deformation of ceramic articles: the characteristics of the raw materials (chemical, phase, and size dispersion composition) and of the intermediate product (uniformity), parameters of drying and calcination (temperature uniformity, gas-dynamic regimes, charging, and so forth).

The creation of a stable framework from relatively large grains, the use of fluxes with high melt viscosity, and accurate prediction of phase-formation make it possible to decrease deformation by adjusting the composition of the raw materials. The use of formation methods that give an intermediate product with high uniformity (slip casting, isostatic pressing) makes it possible to avoid nonuniform shrinkage of articles which occurs because of density nonuniformity and texturing of the intermediate product. Improvements of the equipment used for heat treatment and optimization of its parameters for a concrete material and shape of articles as well as the use of special charging techniques all help to decrease deformation at these stages. The possibilities of all of these methods of decreasing deformation are always limited by the material and the specific product, but one other important tool is remains — adjustment of the shape of an article.

In the conventional technology working forms are fabricated in steps — first a rough and then the final model. If an article undergoes unacceptable deformation during calcination, then dimensions of the model must be adjusted and all steps must be repeated. The time expended on adjustment and fabrication of forms can be greatly reduced by means of computer models, which are used together with CNC machine tools to remove burrs. CAD and CAE programs are used to develop such programs; this requires knowledge of the basic characteristics of the article being calcined.

The volume-stress state of an article during calcination is determined by the temperature field, shrinkage, phase transformations of the material, and other factors. The rheological behavior of the material during calcination can be described by one of the known models taking account of the factors indicated.

The procedure for calculating the inelastic deformation of ceramic articles is given in the monograph [1], where relations for the elastic deformations of the structural elements are modified in the equations of so-called effective viscosity, essentially reflecting the Newtonian behavior of the liquid. The method can be used to assess the tendency toward residual deformation of a material under different types of loads. The method of investigating high-temperature deformation during bending is widely used for this purpose [2].

Only relatively few works are devoted to the study of the deformation of porcelain articles containing a large quantity of fluxes. The tendency toward deformation of different forms of porcelain by the cantilevered rod method is investigated in [3]. Only qualitative conclusions were drawn on the basis of the results obtained.

The more complete investigation in [4] simulates by means of finite-element analysis the deformation behavior of porcelain plates, formed by isostatic pressing, on the basis of the temperature dependence of Young's modulus. The phenomenology of the sintering process is also described, and the real changes in the dimensions of articles are compared with the nominal characteristics. The author's of [4] attribute a sharp increase of Young's modulus to active formation of primary mullite, which decreases the rate of shrinkage of the material. Corrections which are introduced into the calcula-

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tions for rubbing of the legs of a plate, undergoing calcination, against a refractory part make it possible to obtain almost complete agreement between the deformation of the center of the plate bottom (sag) and its edges (rise).

Porcelain plates and ceramic sanitary ware were investigated and modeled in [5], where the dimensions of the articles at different stages of calcination were interpolated, using the equations of diffusion sintering and grain growth and taking account of the temperature gradient, gravity, and the effect of rubbing against refractory parts on the shrinkage of the articles. Good agreement of the results was obtained. The models were tested on other objects, including parts made of construction-grade ceramic.

Most of the experiments described were performed using loading schemes for bending; they are convenient for classifying materials according to their tendency to deform. Bending tests can be applicable for performing analytical calculations of the deformation during calcination of thin-wall intermediate products.

The effect of a glaze coating was not taken into account in works devoted to modeling the deformation of plates [5]. This is a substantial drawback, since a glaze can have large effect on the deformation of an intermediate product [6].

High-temperature compression and tension tests on samples, for example, measuring the longitudinal and transverse dimensions of a sample during calcination under a constant or cyclic load, make it possible to determine the shear or volume viscosity. The dependences of these coefficients on the stress and temperature determine the rheological properties in the equation of sintering (deformation) for continuous media [7]. A drawback of the compression and tension tests is that the uniaxial deformation must be converted to a shear deformation, which for materials with a complex structure introduces uncertainties into their parameters. Another substantial drawback is that tension and compression deformations can differ substantially for the same material [8]. It is very important to take this difference into account in models of articles which have a complicated shape, since compression deformation and solely tensile deformation can arise, for example, in the handle of a teapot. In addition, it is necessary to study the deformation under a load separately from deformation caused by sintering of a material (shrinkage).

Testing with a torsion load is rarely used because of the difficulty of implementing the loading scheme. The main value of such a test is that it makes it possible to obtain rheological data directly by pure shear and without superposing deformation associated with shrinkage. In view of the fact that finite-element methods of modeling have been under active development in recent years, the expediency of developing methods for investigating deformation based on the torsion of tubes has greatly increased.

The objective of our work is to determine the temperature dependence of the viscosity of sintered ceramic material for different methods of applying a load to a sample. Samples made of soft porcelain and intermediate products, which tend to deform at high temperatures, were investigated. Different types of loading of samples were used: bending, stretching, and twisting. The deformation measured in the course of calcination was converted into a value of the viscosity be means of the relations presented in [1].

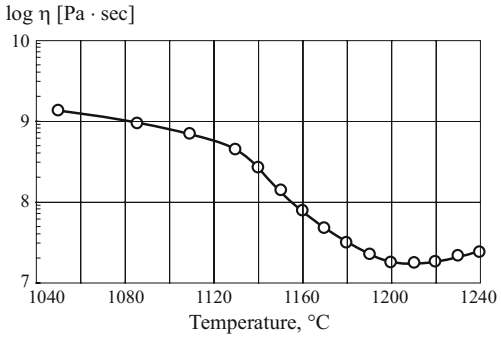

Fig. 1. Logarithm of the effective viscosity η versus temperature for a sample of soft porcelain with cantilevered loading under its own weight.

The tests performed on cantilevered soft porcelain samples, whose deformation was measured visually according to their sagging, yielded the temperature dependence of the logarithm of the effective viscosity (Fig. 1). Shrinkage had a large effect on the deformation of the samples. Sharp deformation, associated with intense dissolution of whitlockite and increase in the amount of feldspar melt in the main mass of the glass, was observed at temperatures 1180 – 1250°C [9]. The viscosity increased only negligibly in the temperature interval 1220 – 1250°C; this is due to the increase in the amount of the secondary mullite, which already appears at 1100°C, and at 1200°C it undergoes further crystallization with growth of needle-shaped grains up to 3 – 4 μm.

The cantilevered loading scheme is convenient for studying the deformation of glazed samples. Here there is no need to take account of shrinkage, which is necessary for loading under compression and tension.

The measurement of deformation under a tensile stress was investigated on samples suspended on a refractory support. Samples of densely sintered corundum served as weights. The tensile stress in this method of loading did not exceed 15 kPa. The deformation of the samples was recorded by means of the positions of markers placed at the center of each sample.

When the semi-porcelain samples were placed under a small tensile load, the viscosity changed monotonically with increasing temperature (Fig. 2), which made it impossible to separate the critical sections in the deformation behavior of the samples. Much more information can be obtained by investigating the torsional deformation of samples in the form of thin-wall plates (Fig. 3). A sample was placed into a specially constructed setup which made it possible to apply a prescribed torsional stress to one end of a thin-wall tube. The thickness of the wall of the clamped ends of the sample was made to be 3 – 4 times greater than that of the working tube, so that the stresses at the clamping sites were less than the as-

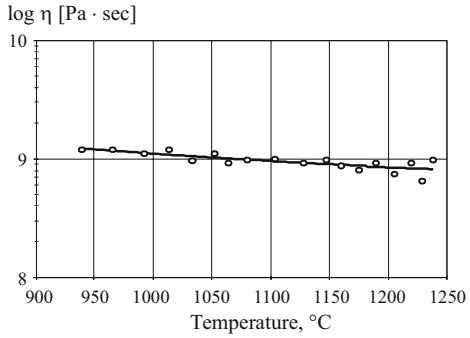

Fig. 2. Logarithm of the effective viscosity η versus temperature for a sample of semiporcelain with tensile load 12 kPa.

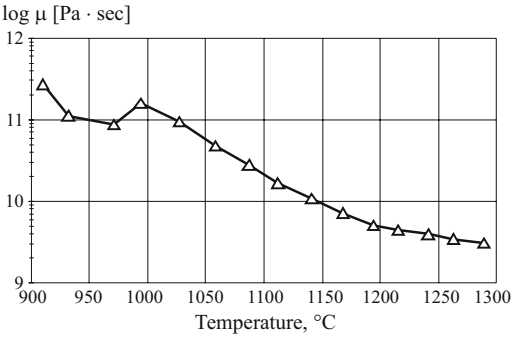

Fig. 4. Logarithm of the dynamic viscosity μ versus temperature for a sample of semiporcelain with torsion under load 140 kPa.

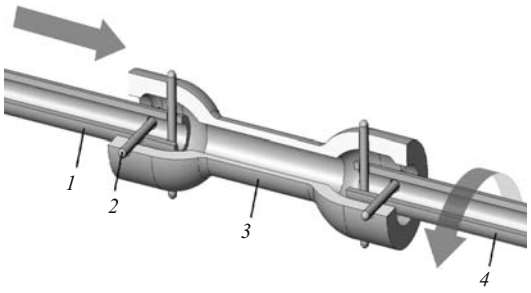

Fig. 3. Scheme of sample testing for torsion: *1*, *4*) corundum tubes transmitting the force on the sample; *2*) corundum pins fixing the sample; *3*) sample.

sumed yield stress. It is important that the shape of such samples did not become distorted during the tests, and rotational deformation occurred only on the thin-wall sample. Using a stepping fixing arm it is possible to set compression and tension components in the sample. The deformation was read visually according to the turn angle of pointers secured to the corresponding elements of the holders.

The dynamic viscosity μ at a section was calculated using a modified Newton's relation:

$$\mu = \frac{F(T)}{S(T)} \frac{l(T)\Delta\tau}{r(T)\Delta\theta},$$

where F is the torsion force developed in the section S of a sample with radius r and length l; $\Delta\tau$ and $\Delta\theta$ are the increment of time and turn angle of the rotating pointer, respectively; and, T is the temperature.

The yield stress of the material can be determined and the critical sections can be found by applying different loads (Fig. 4). In this way a substantial drop of the viscosity was found in the temperature interval 920 – 970°C, which is due to the appearance of a eutectic.

In summary, by studying the deformation behavior of samples of semiporcelain and porcelain under different types of loads it is possible to measure the effective viscosity of materials that is required to construct rheological models and a phenomenological description of sintering processes.

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